The latest catalogue of Gravitational Wave by LIGO-Virgo-KAGRA collaboration

(A quick catch-up to GW Observations)*

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Abstract

The merger of binary black holes or binary neutron stars generates gravitational waves (GWs). The first direct observation of this kind was reported in September 2015 by LIGO (Laser Interferometer Gravitational-Wave Observatory) in the United States. Since then, the joint LIGO, Virgo (Europe), and KAGRA (Japan) collaboration has developed increasingly sensitive detectors, and on May 26, 2026 announced its latest achievement, the catalog *GWTC-5.0*. The number of detected GW events now exceeds 300. This paper outlines the kind of message researchers are conveying to the general public.

Biography

A researcher specializing in general relativity (theoretical physics) and cultural studies of astronomy. His research spans a wide range of fields, including black holes, gravitational waves, cosmology, and the history of astronomy and mathematics. From 2017 to 2021, he led the KAGRA project (Japan's gravitational-wave observatory) as chair of the KAGRA Scientific Congress. He has written and published numerous undergraduate textbooks and popular-science books.

1 Observations of Gravitational Waves (GWs)

General relativity is the theory of gravity constructed by Albert Einstein alone in 1915. This theory explains the origin of gravity not as Newton's law, i.e. the universal attraction exerted by massive bodies, but as the distortion (curvature) of spacetime caused by massive bodies. At the time Einstein arrived at this idea, the only observational evidence supporting it was the precession of Mercury's perihelion, which explained a then-unaccounted-for discrepancy of 43 arcseconds per century between the Newtonian prediction and the actual observations. Later, in 1919, observations made during a total solar eclipse showed that the light from stars passing close to the Sun appeared shifted from its usual position, confirming that the light's path is bent by the distortion of space. In this way general relativity came to be accepted.

General relativity predicts the existence of black holes, an expanding universe, and the existence of GWs. Here, we introduce the topic of GWs, especially on the latest information on GW

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observations.

1.1 GW Observation Network

GW observations are carried out using laser interferometers with arms several km long. Four such observatories currently exist worldwide, carrying out joint observations in coordination. Figure 1 shows photographs and diagrams of the four GW observatories, and Table 1 lists the positions of the four sites. The United States operates two 4-km-arm interferometers called LIGO, located in Hanford, Washington, and Livingston, Louisiana. Europe operates a 3-km-arm laser interferometer nicknamed Virgo near Pisa, Italy. Japan built a 3-km-arm laser interferometer called KAGRA in Kamioka, Gifu Prefecture. KAGRA was built about 20 years after the LIGO, Virgo interferometers; to suppress ground vibration it was built inside tunnels dug into a mountain, and new technology to cool the entire apparatus to cryogenic temperatures has been introduced to reduce thermal noise.

LIGO-Virgo has carried out joint observations from the beginning, joined from 2020 onward by KAGRA as well (hereafter abbreviated as LVK) – this is because, with only a single detector, it is difficult to determine whether a captured signal originates from a GW or from noise caused by instrumental vibration, whereas simultaneous observation by multiple detectors (using a triangulation-like method that includes the signal arrival time difference) makes it possible to estimate where on the sky the GW source is located.

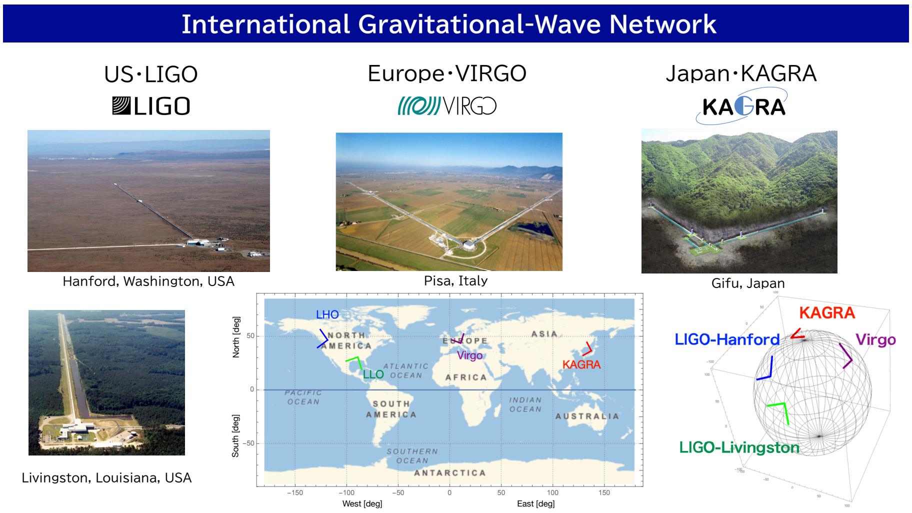

Figure 1: The network of gravitational-wave observatories.

Table 1: Positions and arm orientations of the gravitational-wave laser interferometers
(For example, N 36° W denotes a direction rotated 36° from north toward the west.)

Interferometer	Location	Arm length (km)	Latitude	Longitude	X-arm	Y-arm
LIGO Hanford	USA	4	46°27′19″ N	119°24′28″ W	N 36° W	W 36° S
LIGO Livingston	USA	4	30 33 46 N	90 46 27 W	W 18° S	S 18° E
Virgo	Europe	3	43 37 53 N	10 30 16 E	N 19° E	W 19° N
KAGRA	Japan	3	36 24 36 N	137 18 36 E	E 28.3° N	N 28.3° W

Table 2 shows the observing runs and Figure 2 shows plans currently made public. To date, four observing periods – from O1 (Observing Run 1) through O4 – have been scheduled for joint observation. Between observing periods, each observatory has improved its equipment, gradually extending its observable distance. The performance of a GW observatory is expressed as the observable distance – how far away a source can be detected (with a signal-to-noise ratio of 8 or higher) – for the GWs produced by a typical binary neutron star merger. The values in Mpc shown in Figure 2 are these distances.

At present, O4 has ended, and each observatory is upgrading its instruments in preparation for the next O5. The observing run IR1, to be carried out for six months starting in November 2026, is a trial run ahead of O5.

Table 2: Observing Runs (dates shown in UTC).

Run	Advanced LIGO		Advanced Virgo		KAGRA	
	yyyy mm dd	yyyy mm dd	yyyy mm dd	yyyy mm dd	yyyy mm dd	yyyy mm dd
O1	2015 9 12 –	2016 1 19	–		–	
O2	2016 11 30 –	2017 8 25	2017 8 1 –	2017 8 25	–	
O3a	2019 4 1 –	2019 9 30	ditto		–	
O3b	2019 11 1 –	2020 3 27	ditto		(O3GK) 2020 4 7 –	2020 4 21
O4a	2023 5 24 –	2024 1 16	–		2023 5 26 –	2023 6 25
O4b	2024 4 10 –	2025 1 28	ditto		–	
O4c	2025 1 29 –	2025 11 18	ditto		2025 6 6 –	2025 11 18

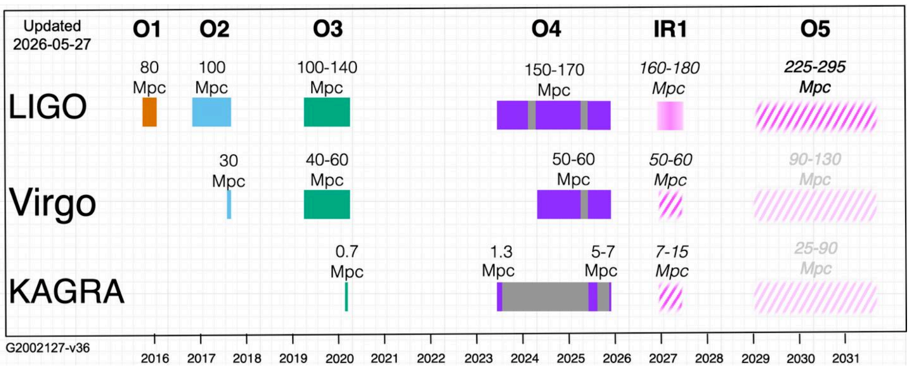

Figure 2: LVK Observing Run Plans. (from `https://observing.docs.ligo.org/plan/`)

1.2 Latest Catalog GWTC-5.0

We name GW events after the date and time at which they were detected, expressed in Coordinated Universal Time (UTC). For example, a GW event detected at 16:24:26 UTC on January 5, 2020 is denoted GW200105_162426. (Note that for sufficiently exceptional events such as GW150914 or GW250114, the time stamp is sometimes omitted here to make the text easier to read.)

At the end of each observing run, LVK has compiled and released the GWs believed to originate from compact-binary mergers as a transient GW catalog, GWTC. The most recent catalog, GWTC-5.0, released on May 26, 2026, covers data through the O4b observing run. The data can be obtained from the Gravitational-Wave Open Science Center (GWOSC) website (`https://gwosc.org/`).

GWTC is a cumulative catalog. GWTC-5.0 includes not only the new results observed in the previously unpublished O4b data but also all the results of every earlier catalog. Starting with GWTC-5.0, every detected candidate GW signal is labeled with the prefix "GW," even if it may not be of astrophysical origin. That said, for a candidate to be included in the catalog, the event must have a high probability (at least 50%) of being of astrophysical origin, and the selection is further narrowed to signals that pass all data-quality and signal-consistency checks.

The number of GW signals included in the catalog is summarized in Table 3. This table tabulates the data for which the binary parameters have been determined. Nearly 300 GW events have been confirmed to date, and thanks to improvements in detector sensitivity, the detection rate has increased.

Table 3: Number of GW events included in the Gravitational-Wave Transient Catalog (GWTC).

		released	arXiv	ref.	BHBH	NSNS	NSBH	unknown	total
GWTC-1	O1+O2	2018/Dec 3	1811.12907	PRX 9 (2019) 031040	10	1			11
GWTC-2	O3a	2020/Oct 28	2010.14527	PRX 11 (2011) 021053	36	1		2	39
GWTC-2.1	+	2021/Aug 2	2108.01045		+8-3				5
GWTC-3	O3b	2021/Nov 5	2111.03606	PRX 13 (2023) 041039	32		3		35
GWTC-4	O4a	2025/Aug 25	2508.18082		86				86
GWTC-5	O4b	2026/May 26	2605.27225		104				104
				total	268	2	3	2	280

Table 4 summarizes the GW events that researchers have focused on to date. For the general public, the news that has resonated most is probably either GW150914 (the GW from a binary black hole merger), described as "the first direct detection of a GW" or GW170817, which captured the first binary neutron star merger.

- GW150914 was announced in February 2016 by the American LIGO group as the "first GW observation." The two LIGO interferometers detected the same gravitational waveform 6.9 milliseconds apart, and from this time difference it was determined that the wave arrived from the southern sky. The waveform, shown on the left of Figure 3, rises in frequency from 35 Hz to 250 Hz before rapidly decaying. It closely matches the waveform predicted in advance by simulations, and from it we learned that two black holes with masses 36 and 29 times the solar mass merged, producing a single black hole of 62 solar masses after the merger. The missing mass, equivalent to three solar masses, was radiated across the universe as GW energy (here we use the mass-energy equivalence formula $E = mc^2$). Given the strength of the GW observed on Earth, this binary-black-hole merger was determined to have occurred 1.3 billion light-years away.
- GW170817 was the first observed merger of a binary neutron star system. Because a black hole is not formed immediately after the merger, an explosive event of hot nuclear matter occurred after the collision, which continued to shine for weeks afterward – a phenomenon called a kilonova, up to 1000 times brighter than an ordinary supernova. Within about six minutes of the GW detection, the LIGO-Virgo group recognized that this was a neutron-star merger, and within four hours had narrowed down the source's position to 39 square degrees on the sky and distributed the observational information to observatories worldwide. More than 70 observatories and satellite-borne telescopes around the world pointed their instruments in that direction, and simultaneous observations were carried out across a wide range of wavelengths, including gamma rays, X-rays, visible light, infrared, and radio waves. This marked the start of the comprehensive multi-wavelength observation, so-called multi-messenger astronomy, in which a single astronomical phenomenon is tracked from many angles using different telescopes. As a result, it was found that gamma rays were observed 1.7 seconds after the merger, and that the source was the galaxy NGC4993, located 40 Mpc away; by comparing the day-by-day dimming of the light with simulations of neutron-star binary mergers, it was also confirmed that the r-process nucleosynthesis of atomic nuclei occurred immediately after the merger, just as predicted. The gamma-ray observations immediately after the merger tested models of the post-merger explosion, and the determination of the source's distance, combined with the difference between the arrival times of the GW and the light, has also been used to

test general relativity and models of cosmic expansion.

To date, the only GW whose source location has been pinpointed is GW170817. It has become clear that binary neutron star mergers occur less frequently than originally expected.

At the time of the recent GWTC5 announcement, the following three GW events attracted particular attention.

- GW250114 – The Largest GW Event to Date
  GW250114 is the most powerful GW signal ever recorded from a binary black hole merger. The "magnitude" of a GW event is expressed by its signal-to-noise ratio. The previous record was a signal-to-noise ratio of 42.4 for GW230814, but GW250114 has a signal-to-noise ratio of 76.9 (nearly twice as large), which has made possible a stringent test of general relativity and a check of the validity of Hawking's area theorem of black hole.
- GW241011 and GW241110 – Evidence of Hierarchical (Multiple) Mergers
  Two black holes originating from stars that were born as a binary, evolved together, and each formed a black hole are expected to have spin angular momenta that are, to some degree, aligned with the orbital rotation direction (similar to how many planets in the solar system rotate in the same direction). However, GW241011 and GW241110 defied this expectation, showing precisely measured spin angular momenta together with markedly unequal mass ratios. These are clues suggesting that they may have formed in a crowded environment such as a dense star cluster, where black holes can dynamically encounter and capture one another, and the remnants of past mergers can merge again. These GW events are, at present, the best evidence for so-called "hierarchical (multiple) mergers."
- GW240925 – First Use of an Astrophysical Event for Detector Calibration
  Detecting GWs requires precise calibration of the detector at the moment each event is captured. Normally the calibration state is well understood, but sometimes it takes time for a detector's state to "settle" after a change, leaving the calibration uncertain in the meantime. GW240925 was detected while the instrument was in such an unsettled state. The event itself was a typical binary black hole merger (with component masses of about 9 and 7 solar masses), but the LIGO Hanford detector was poorly calibrated at the time. Fortunately the signal was quite strong (signal-to-noise ratio 31.9), and the waveform of GWs from black hole mergers is well understood, so we were able to compare the poorly calibrated data against the theoretical model. This made it possible to work backward from the signal itself to determine the detector's calibration, making it the first instance in which an astrophysical GW event was used directly to calibrate a detector.

2 What GW Observations Reveal

2.1 What We Learn from the GWs of Compact-Binary Mergers

Ten years after the first detection, the nature of GW reporting has shifted qualitatively – from "we were able to observe it" to "this is what the observational statistics reveal."

Figure 3 shows the predicted waveform produced by a compact-binary merger. Before merger, the binary gradually spirals inward while emitting GWs, generating a GW whose amplitude gradually grows and whose frequency gradually rises. This waveform, resembling birdsong, is called a chirp signal. By comparing this part of the waveform with simulations, we can determine the masses and spins of the two stars making up the binary, as well as the inclination of the binary's orbital plane. If the binary includes a neutron star, tidal forces deform the neutron star, and this effect is expected to appear in the gravitational waveform. By examining the waveform in detail, we expect to learn the equation of state of the ultra-dense nuclear matter that makes up a neutron star – information that is beyond the reach of any terrestrial experiment. If the

Table 4: Notable events among those observed (from the fifth Gravitational-Wave Transient Catalog (GWTC-5), as of May 26, 2026). Abbreviations: GW (gravitational wave), BH (black hole), BBH (binary BH), NS (neutron star), BNS (binary NS).

event	note
GW150914	The first directly observed GW event ever reported. It established the existence of BBHs and provided the first confirmation of BHs with masses exceeding 30 times the solar mass ($M_\odot$).
GW170817	The first reported BNS event. Extensive follow-up observations immediately afterward made it the first successful example of multi-messenger astronomy. The constraint on the NS equation of state derived from the GW waveform, expressed as the pressure at twice the nuclear saturation density $\rho_{\rm nuc} = 2.8 \times 10^{14}$g/cm^3, is $2\rho_{\rm nuc} = 3.5^{+2.7}_{-1.7} \times 10^{34}$dyn/cm^2 (90% credible interval). Because the gamma rays arrived 1.7 seconds after the GW peak, the fractional deviation of the GW propagation speed from the speed of light was constrained to be below 1×10^{-15}. In addition, optical and infrared follow-up observations revealed evidence for the synthesis of heavy elements beyond iron, suggesting that this is an important channel for r-process nucleosynthesis.
GW190412	A GW from a BBH with a clearly large mass ratio, for which detection of higher-order GW modes was attempted.
GW190425	The second BNS discovered.
GW190521	A BBH whose post-merger total mass is estimated at about $150M_\odot$, marking the first discovery of a candidate object in the so-called intermediate-mass BH regime.
GW190814	Thought to be a GW from a compact object in the 2–$5M_\odot$ mass range (the "mass gap"), a range considered impossible to produce under standard star-formation scenarios.
GW200115	The first event reported with high confidence as an NS-BH merger.
GW230529_181500	Detected only by LIGO Livingston; a merger of components with masses 1.2–$2.0M_\odot$ and 2.5–$4.5M_\odot$, one in the NS mass range and the other in the mass gap.
GW230627_015337	The lowest-total-mass BBH, at $5.78M_\odot$.
GW231123_135430	The BBH with the largest total mass, with a post-merger mass estimated at 190–$265M_\odot$. One BH is a rare, high-mass object exceeding the mass gap produced by pair-instability supernovae, while the mass of the other falls within the mass gap; both are estimated to have high spins, suggesting, as with GW190521, a second-generation BBH merger.
GW240925 & GW250207	The first instances in which detector calibration was carried out using an actual signal.
GW241011 & GW241110	BBHs whose spin orientation and magnitude, together with markedly unequal mass ratios, suggest the possibility of hierarchical (multi-generation) mergers.
GW250114_082203	The "strongest" GW observed to date, with the highest signal-to-noise ratio on record. Although its parameters as a BBH are comparable to those of GW150914, improvements in instrument sensitivity enabled a stringent test of general relativity.

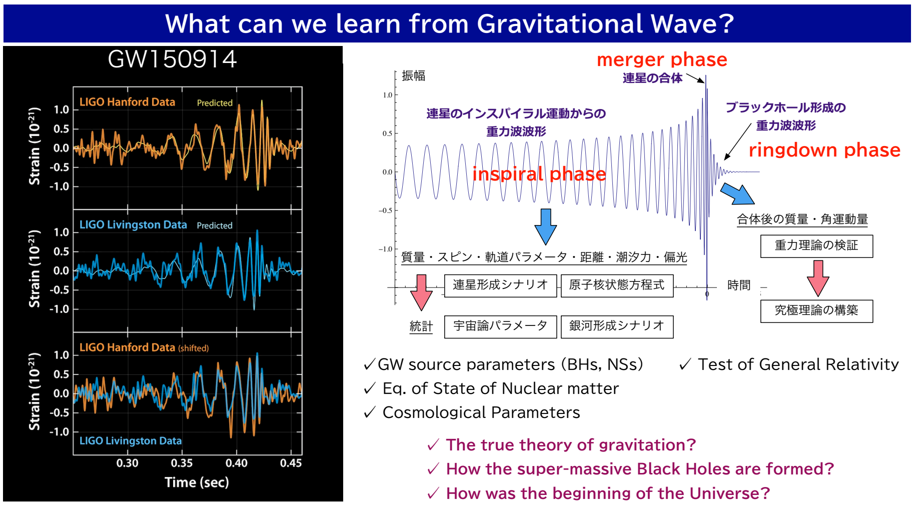

Figure 3: What can we learn from GW?

binary merges and a black hole forms immediately afterward, the GW is swallowed by the black hole and decays rapidly. If this decaying portion is observed, it reveals the mass and spin of the finally formed black hole. General relativity predicts that several modes should exist in this decaying (ringdown) waveform, and whether multiple modes are actually observed provides a test of general relativity. Since the tests of general relativity carried out so far involve gravity at the scale of the solar system, being able to test general relativity in a much stronger gravitational field – the extreme phenomenon of a black hole merger – is an important step toward building the next stage of physics, including quantum gravity.

Furthermore, by analyzing the statistics of individual GW observations, it also becomes possible to test models of star and black-hole formation and to analyze the parameters of cosmic expansion.

At present, the Hubble constant, which characterizes the expansion of the universe, has been reported to differ between two observational methods by more than the statistical error. One method uses the cosmic microwave background radiation (CMB), an estimate based on data from just 380,000 years after the birth of the universe. The other method estimates the universe in the vicinity of our own galaxy using data from supernova explosions. This latter method, since the mechanism of a typical supernova explosion is well known, measures distance from the brightness of the supernova explosion – that is, it treats supernovae as “standard candles.”

Measuring cosmic expansion through GW observations constitutes a third method. Using binary neutron star mergers that generate GWs, and measuring the distance to each by its waveform, it could be described as treating the GW source as a “standard siren.” The Hubble-constant discrepancy may ultimately be resolved by GW observations in the future.

2.2 What We Have Learned So Far from the GWs of Compact-Binary Mergers

Figure 4 presents, in terms of their mass composition, the compact-binary mergers reported to date. Northwestern University’s plotter was used to generate it. Each pair of points connected vertically by a blue line represents one binary-system merger, and these are arranged from left to right in order of increasing total mass.

Let us read from this figure what remains a mystery today.

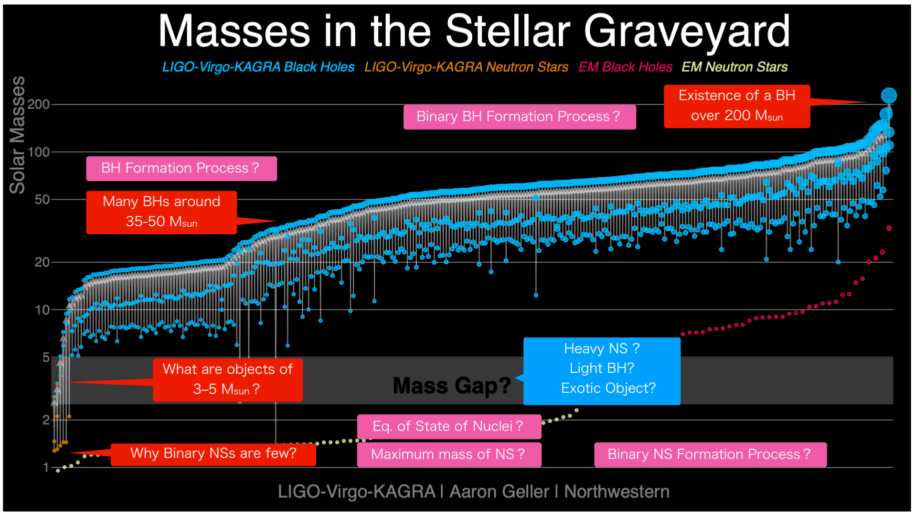

Figure 4: The masses of the compact-binary mergers observed as GW sources to date, arranged in increasing order, using Northwestern University's plotter output, modified for this figure.

Studies of the nuclear equation of state suggest that the maximum mass of a neutron star is roughly two to three times the solar mass. Star-formation theory, on the other hand, suggests that black holes formed at the final stage of stellar evolution have masses of roughly 5 to 90 times the solar mass. In other words, there should be no compact object capable of generating GWs with a mass between three and five solar masses – this is called the mass gap. However, GW observations have, in a few cases, reported merger waveforms from binaries with masses that fall within the mass gap. It seems this must be either an error in existing theory, or evidence for the existence of objects we do not yet know about.

Also, most of the GWs observed so far have originated from binary black hole mergers, and the fact that binary neutron stars are fewer than expected is itself a problem. Furthermore, looking at the sources of the observed GWs, black holes with masses of 35 to 50 times the solar mass account for the majority. This may partly be because GW detectors are optimized for observing GWs in the 100-500Hz range, but future changes in the statistics deserve attention. Among high-mass binaries, black holes exceeding 200 times the solar mass have been reported. This is probably the result of so-called "hierarchical (multiple) mergers," in which large black holes formed by earlier mergers merge again with one another. How this connects to the formation process of the supermassive black holes at the centers of galaxies will be a research topic going forward.

2.3 Outreach from GW Observation Groups to the Public

LVK groups take a variety of approaches to bring the benefits of their research back to society. There are the Education and Public Outreach group and the Communication Division group, which work together on public outreach and press announcements through the media.

Let us look at the main sources of information.

- LVK websites and SNS (social media) posts from each group
  LIGO: `http://www.ligo.org/`
  Virgo: `http://www.virgo-gw.eu/`
  KAGRA: `https://gwcenter.icrr.u-tokyo.ac.jp/en/`
  Ozgrav: `https://www.ozgrav.org/`

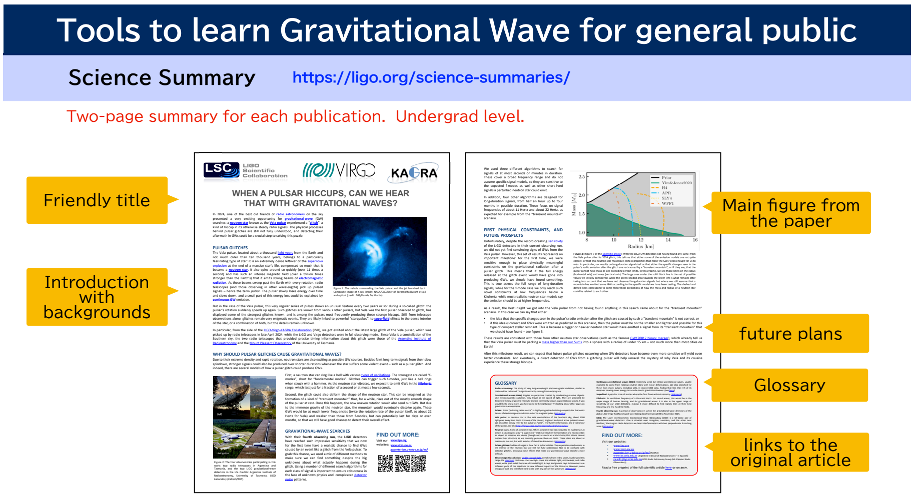

Figure 5: Format of the Science Summary. For each paper published, a 2–3 page document explaining the overview is prepared for the general public (at a level suitable for high school through university students).

LIGO-India: `https://www.ligo-india.in/`

- The list of papers, and, for each publication, an explanatory summary of its abstract (called a Science Summary) are published. Science Summary is prepared in the style shown in Figure 5, with translations into various languages also being prepared.
  Science Summary: `https://ligo.org/science-summaries/`
  Paper list (LIGO): `https://pnp.ligo.org/ppcomm/Papers.html`
  Paper list (Virgo): `https://www.virgo-gw.eu/publications/`
- Publication of Gravitational-Wave Data, and Workshops for Its Use
  Gravitational-Wave Open Science Centre: `https://gwosc.org/`
  GW Open Data Workshops: `https://gwosc.org/workshops/`
- Plotters Provided for Publicly Available Gravitational-Wave Data
  Plotter (Northwestern Univ.): `https://media.ligo.northwestern.edu/gallery/mass-plot`
  Plotter (Cardiff Univ.): `https://catalog.cardiffgravity.org/`
- Newsletter Publication
  LIGO Magazine: `https://ligo.org/magazine/`
- Links to Various Resources
  LIGO: `https://ligo.org/education/`
  Virgo: `https://www.virgo-gw.eu/resources/`
  LIGO-Lab: `https://www.ligo.caltech.edu/page/educational-resources`
- Workshops for Educators
  LIGO-Hanford: `https://www.ligo.caltech.edu/WA/page/lho-educators`
  LIGO-Livingston: `https://www.ligo.caltech.edu/LA/page/Educators`
  Virgo: `https://www.virgo-gw.eu/get-involved/teachers-program-2/`
- Public Science Centers
  LIGO-Hanford: `https://www.ligo.caltech.edu/WA/page/lexc`
  LIGO-Livingston: `https://www.ligo.caltech.edu/LA/page/Science-Education-Center`

3 The Future of GW Observations

Going forward, as more GWs are observed, it will become possible to address physical questions that have until now been out of reach – not only characterizing the source objects (determining parameters such as mass, spin, and orbit) but also understanding the state of the ultra-dense matter inside neutron stars and how far general relativity remains correct.

Future plans are also underway to observe GWs from space. The European Space Agency (ESA) has begun the LISA mission, which will consist of a laser interferometer with a baseline of 2.5 million km formed by three satellites, which are planned to be launched around 2034. Because a long-armed interferometer can capture GWs at lower frequencies than ground-based detectors, it will not only provide advance warning for ground-based GW detections but will also make it possible to detect GWs from mergers of much more massive black holes. The origin of the supermassive black holes at the centers of galaxies remains unknown, but accumulating statistics from GW observations should also help clarify how such supermassive black holes came to form.

Everything discussed so far has centered on GWs generated by compact-binary mergers. However, because a GW is a ripple in spacetime itself, it passes through any matter that lies in its path. At present, the limit of what astronomical observation can reach is the cosmic microwave background radiation – information from the stage at which the plasma settled and light was first able to travel in a straight line, that is, 380,000 years after the Big Bang. In other words, we cannot obtain information from the period before those first 380,000 years after the Big Bang. GWs, however, should carry information from that era as well, and are expected to offer clues to unraveling the conditions of the early universe.

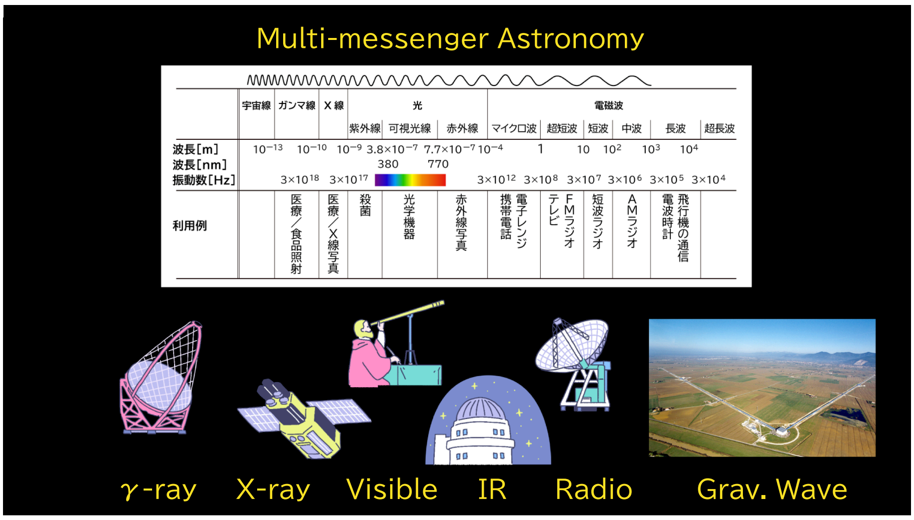

Figure 6: The network of gravitational-wave observatories.

Four hundred years have passed since Galileo built his telescope and observed the universe. Since then, in addition to visible light, humanity has developed ways to observe the universe using infrared, radio waves, X-rays, gamma rays, neutrinos, and other means. Gravitational waves are the next “eye” (or “window”) in that succession (Figure 6). We hope many people will take an interest in this field, and we would like to share its achievements with them.